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NEUTRON TRANSITION MOMENTS AND QUADRUPOLE *T*- OR *F*-VECTOR STATES

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A study of low-lying 2^+ states by proton and deuteron inelastic scattering from ^{104}Pd, ^{110}Pd, ^{112}Cd, ^{146}Nd, ^{150}Nd and ^{150}Sm is described. Evidence of neutron components in the excitation of 2^+ states lying between 2.2 and 3.0 MeV in Pd and Cd isotopes has been obtained. This result is consistent with the predictions of the IBM-2 model for mixed-symmetry states.

The dynamical properties of nuclear states are described by proton and neutron transition multipole moments M_p and M_n. The former are directly obtained as the square root of the electromagnetic (EM) transition rates and are much better known than the neutron multipole moments M_n, which can be derived by comparing the inelastic scattering of different probes. The method is based on the different interaction between the probe and target protons (p) and neutrons (n). This procedure has been proved consistent, at least for the available data, which are mostly limited to the lowest 2^+ state, and systematic variations in M_n and M_p values have been found [1]. A renewed interest in this topic is connected with the recent prediction of a new class of low-lying collective states. These are described in the geometrical models as *T*-vector or isovector states [2], and in the IBM-2 model as the so-called mixed-symmetry states, classified by a new quantum number, the *F*-spin, analogous to the isospin T [3]. For these states M_p and M_n are predicted to be of opposite sign [2,4]. The existence of mixed-symmetry states (J^{π}_m) has been so far found only in the case of 1^+_m states in deformed nuclei [5]. Recently several attempts to identify the 2^+_m states have been reported. The third 2^+ state in $N=84$ isotones, in ^{150}Sm and in ^{56}Fe has been considered as a 2^+_m candidate [6-8]. Identification of mixed-symmetry strengths and of its possible spreading over the dense quasi-particle background is presently discussed [4,9]. Further experimental investigations are therefore highly desirable.

The present method is based on the comparison between (p,p′) and (d,d′) cross sections to different 2^+ states. As will be shown below, an anomalous $\sigma(\mathrm{p,p'})/\sigma(\mathrm{d,d'})$ ratio indicates either a *T*- (*F*-) vector state or a state with a dominant n (p) component. In both cases these are predicted to be excited differently in (p,p′) and (d,d′) reactions. A 2^+ state equally excited by the two probes cannot, on the other hand,

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have a sizeable T- (F-) vector component.

Differential cross sections have been measured for proton and deuteron scattering on ^{104,110}Pd, ^{112}Cd, ^{146,150}Nd and ^{150}Sm at 30.3 and 50.4 MeV, respectively. Enriched targets, with a thickness of the order of 1 mg/cm^2, have been used. The scattered particles were detected in the focal plane of the KVI QMG/2 magnetic spectrograph. A low incident energy has been chosen to obtain a relatively good energy resolution. The overall energy resolution was 12 keV and 15 keV in (p,p′) and (d,d′) measurements, respectively. At these incident energies the excitation of a 2^+ state via a two-step process cannot be completely neglected. To allow an easy comparison between proton and deuteron cross sections, the (d,d′) experiment has been performed at an incident energy at which the ratio of two-step to one-step contributions, as predicted by coupled-channels calculations for E2 excitations, is about equal to that predicted in the case of 30.3 MeV protons. Transitions up to an excitation energy of 3.2–3.5 MeV have been studied. Differential cross sections have been measured down to a minimum value, corresponding to a B(E2) value of 6 e^2 fm^4. The angular distributions in some cases differ significantly from that of the first 2^+. This can be due to a relevant two-step excitation or to a particular transition form factor. Different form factors shapes for 2^+ transitions have been found in electron scattering experiments on Pd isotopes [10]. The (p,p′) and (d,d′) cross sections, corresponding to a given level, when plotted against KR (K and R are, respectively, the transferred momentum and the transition radius), are very similar, as shown in fig. 1. This permits an unambiguous determination of the ratios σ(p,p′)/σ(d,d′). These ratios are shown in fig. 2. In some cases, the spin identification is not certain or contamination by unresolved levels of a different multipolarity cannot be excluded. These cases are indicated in the figure by crosses.

Evidence of marked changes in cross section ratios is found in ^{104,110}Pd and ^{112}Cd for transitions to excited levels located above 2.2 MeV excitation energy. No such strong changes are found in ^{146,150}Nd and ^{150}Sm. This excludes the presence of any large F-vector component in the last three nuclei. Transitions with a cross section ratio at least 50% different from the average value are reported in table 1. Data concerning the well-known transition to the 2_1^+ state are

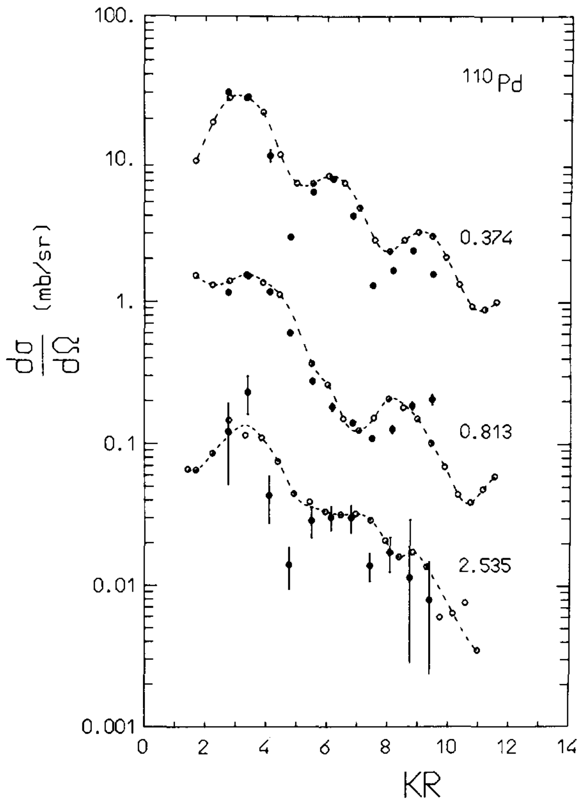

Fig. 1. Differential cross sections for proton (open points and dashed lines) and deuteron (full points) inelastic scattering to 2^+ states of ^{110}Pd. The excitation energies are indicated on the graph. The cross sections are plotted against KR, where K is the transferred momentum and R is the transition radius.

also included and serve as a test of the method.

The transition matrix elements M(p,p′) and M(d,d′), given in columns three and four, are effective transition amplitudes inclusive of two-step contributions. As mentioned above, the relative amount of two-step contributions should be about the same at the energies chosen for the two probes and thus should not affect strongly the ratio of cross sections and of matrix elements. The fact that M(p,p′) is always larger than M(d,d′), with the only exception of the 1.892 MeV level in ^{110}Pd, indicates that the transitions are mostly neutron excitations. Two-step effects can be evidenced by the different shape of the angular distributions (compare for instance those of the 0.813 and 0.374 MeV states in fig. 1). The energy dependence of two-step cross sections is also much steeper. Available (p,p′) data at lower energies from

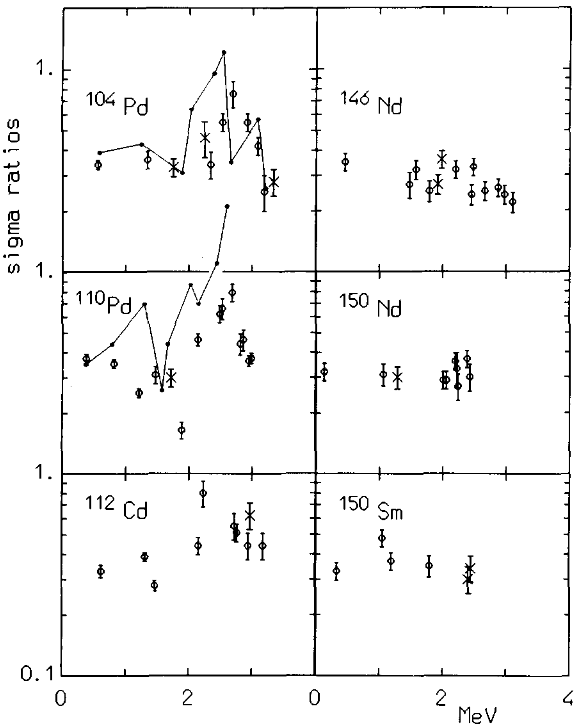

Fig. 2. Ratios of (p,p′) to (d,d′) cross sections for the excitation of 2^+ states, plotted against the excitation energy. The full points connected by lines are the result of IBM-2 calculations.

previous experiments [11–13] and at 60 MeV, collected in the present study, indicate that the transitions with the largest σ-ratios are due completely to direct excitation. Both direct and two-step processes can be present in the transitions to the other states, indicated in table 1 by a star. These will not be considered further since it is not clear in this case which process is responsible for the neutron excitation. We can express the transition matrix elements as a sum of M_p and M_n (properties of the target nucleus) weighted by the interaction strengths (dependent on the probe). Assuming, as usual at the incident energies here considered, an effective p–n interaction three times larger than the p–p interaction, one obtains that the (p,p′) and (d,d′) cross sections are proportional to the square of $M(\mathrm{p,p'})=0.25M_{\mathrm{P}}+0.75M_{\mathrm{n}}$ and of $M(\mathrm{d,d'})=0.5M_{\mathrm{p}}+0.5M_{\mathrm{n}}$, respectively. In the case of collective isoscalar transitions M_p and M_n are of the same sign and order of magnitude and lead to similar values for $M(\mathrm{p,p'})$ and $M(\mathrm{d,d'})$. The ratio of the resulting cross sections is simply determined by spin and kinematical factors and is, in the present case, of the order of 0.37. For a transition with a large isovector component the $M_{\mathrm{p(n)}}$ moments are again of the same order but of opposite sign [2,4], and consequently the ratio $\sigma(\mathrm{p,p'})/\sigma(\mathrm{d,d'})$ can be very large. From the above relations one obtains $M_{\mathrm{p}}=3M(\mathrm{d,d'})-2M(\mathrm{p,p'})$ and $M_{\mathrm{n}}=2M(\mathrm{p,p'})-M(\mathrm{d,d'})$. A simple DW analysis cannot give the sign of transition matrix elements. The moments deduced assuming $M(\mathrm{p,p'})$ and $M(\mathrm{d,d'})$ of different sign give $B(\mathrm{E2})$ values of the order of 1000 $e^2\,\mathrm{fm}^4$. Such values are very large and, at least in the case of Pd isotopes, contradicted by (e,e′) experiments [10], in which these transitions, when detected, appear with a weak intensity. In the following we consider only the solution obtained assuming $M(\mathrm{p,p'})$ and $M(\mathrm{d,d'})$ of the same sign and positive, which gives the moments reported in table 1. The overall errors in the E2 moments are of the order of 10% for the ratio $M_{\mathrm{p}}/M_{\mathrm{n}}$, of 40% for M_{p} and of 27% for M_{n}. These are due to errors in cross section absolute values and to errors caused by uncertainties in the radial dependence of the transition form factors which are needed to extract the matrix elements. The former are of the order of 10% and lead to an error of the order of 5% in $M(\mathrm{p,p'})$ and $M(\mathrm{d,d'})$; the overall values include also a conservative estimate of the latter which are neglible only for the 2_1^+ states. The similarity of (p,p′) and (d,d′) differential cross sections suggests a similar response of the two probes to the transition form factors and a better accuracy in the determination of $M_{\mathrm{p}}/M_{\mathrm{n}}$ ratios than of their absolute values. A good agreement is found between the M_{p} values for the 2_1^+ states and those from EM data (given in the table between parentheses).

Values of M_{n} much larger than the corresponding M_{p}, as for most of the levels in table 1, can be obtained mixing isoscalar and isovector strengths. In this case it is usefull to define a *T*- (*F*-) scalar $M_{\mathrm{s}}=\frac{1}{2}(M_{\mathrm{p}}+M_{\mathrm{n}})=M(\mathrm{d,d'})$ and a *T*- (*F*-) vector multipole moment $M_{\mathrm{v}}=\frac{1}{2}(M_{\mathrm{p}}-M_{\mathrm{n}})=2[M(\mathrm{d,d'})-M(\mathrm{p,p'})]$.

The T- (F-) vector moments M_{v} quoted in table 1 give $B(\mathrm{E2})$ values ranging from 5 to 32 $e^2\,\mathrm{fm}^4$, i.e. of the order of 0.05–0.25 single particle units, and cannot be considered as a clear signature of the collectivity of these states.

Table 1
Excitation energies and cross section ratios for the 2^+ states indicated. M(p,p′) and M(d,d′) are E2 moments of transition potentials in $e\,\mathrm{fm}^2$ units. M_p, M_n and M_ν are E2 moments of proton, neutron and isovector transitions densities.

Nucleus	E_x (MeV)[a]	σ(p,p′)/σ(d,d′)	M(p,p′)	M(d,d′)	M_p	M_n	M_ν
^{104}Pd	0.556	0.342	87.7	83.5	75.1(73.7)	91.9	
	2.533*	0.553	8.43	7.00			
	2.696	0.764	4.78	3.37	0.55	6.19	−2.82
	2.923*	0.553	6.97	5.63			
^{110}Pd	0.374	0.374	116	107	89.0(93.4)	125	
	1.892*	0.165	3.23	4.36			
	2.496	0.620	10.6	7.77	2.11	13.4	−5.66
	2.534	0.660	8.18	5.58	0.38	10.8	−5.20
	2.691	0.790	7.08	4.81	0.27	9.35	−4.54
^{112}Cd	0.617	0.330	85.9	79.4	66.4(69.6)	92.4	
	2.231	0.800	6.34	4.05	0.53	8.63	−4.58
	2.724*	0.550	9.64	6.91			
	2.766*	0.510	17.0	12.7			
	2.970*	0.620	9.00	6.26			

[a] The star indicates levels which may have two-step contributions.

Geometrical model calculations [2] and simple IBM-2 estimates [14] both predict T- (F-) vector 2^+ states at excitation energies between 2 and 2.5 MeV, with B(E2) values 0.1–0.3 times that of the 2_1^+. This strength is much larger than that found in the present experiment. More detailed IBM-2 model calculations [15,16] result in an F-vector strength of lower absolute value and in some cases mixed with the scalar part. A difficulty is caused by the fact that the strength of the Mjorana force, which is very important in describing mixed-symmetry states, is not determined by the g.s. band data as the other parameters of the model. The values normally used for the three terms describing this force are $\xi_2=0$ and $\xi_1=\xi_3=0.1$–0.3 MeV as in ref. [7], or all three equal [5,15,17], with values from about 0.1 up to 0.4. The first set gives an F-vector strength mainly concentrated in the third or fourth 2^+ level at 1.2–2 MeV which is not in agreement with the present experiment. Equal values of 0.1–0.2, fragment the strength into 2 to 4 levels located between 2.2 and 3.0 MeV even if one of them is often predominant. IBM-2 cross section ratios for ^{104,110}Pd have been calculated following the procedure outlined in refs. [13,18], using the effective charges of ref. [19] and setting the three Majorana terms equal to 0.18 MeV. The other IBM-2 have been have been taken from g.s. band analysis [10,16]. They are shown in fig. 2. Of the other nuclei considered, only ^{112}Cd shows evidence of T- (F-) vector strength. The available IBM-2 model parameters for this nucleus do not have the same degree of confidence and therefore the predicted ratios are not reported in fig. 2. Calculations for Nd and Sm isotopes using the Majorana force, calibrated on the 1_m^+ states which have been found in this mass region [17], predict 2_m^+ states between 2.7 and 3 MeV. At least one of them should be enough excited in proton scattering so to be easily detected. The lack in our data of indications for such strength may be due to a strong mixing with other nearby F-scalar 2^+ levels, as suggested [15] for the transitional nucleus ^{150}Sm. Also a fragmentation larger than predicted, at least in ^{150}Nd and ^{150}Sm, could prevent detection of 2_m^+ states because of the very high level density above 2.5 MeV.

We summarize the present letter by mentioning the following: (i) No evidence of T- (F-) vector 2^+ strength is found for ^{150}Sm and ^{146,150}Nd; (ii) transitions with relatively large neutron components are present in the two Pd isotopes and in ^{112}Cd; (iii) a mixing of scalar and T- (F-) vector components can explain the observed transition moments; (iv) present IBM-2 predictions are in reasonable overall agreement with Pd data.

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